Monitoring of Indoor Radon in Passive House Buildings

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A post occupancy study of indoor radon concentrations in certified Passive House buildings

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ABSTRACT: The acceleration of the climate emergency is having a profound effect on European Union (EU) policy influencing energy efficiency standards and targets. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) and the Emissions Gap Report from the UN have outlined and advocated the use of the passive house standard. This study is both important and original given it is the first research attempt to examine radon distribution in Passive House buildings in Ireland and the UK. The World Health Organization (WHO) has identified radon as a known human carcinogen. Radon is a colourless, odourless and tasteless radioactive gas. It is formed by the radioactive decay of the small amounts of uranium that occur naturally in all rocks and soils. The Passive House standard has two inherent principles which should mitigate against high radon levels. These are Airtightness and Mechanical Ventilation Heat Recovery (MVHR). This research is of significance because it provides evidence of how effective the transferred air principle is with a correctly installed and commissioned MVHR unit in the domestic setting. A striking observation to emerge from the data shows a difference in radon distribution between upstairs and downstairs when compared against regular housing.

Keywords: *Certified Passive House, EnerPHit, Radon, Indoor Air Quality, Energy Efficiency*

1. INTRODUCTION

The UK Parliament became the first in the world to declare a climate emergency on 1st May 2019. The Irish government declared a climate emergency a week later and the Northern Ireland Assembly followed suit in February 2020 [1].

The Paris Agreement, signed in 2016, is an agreement within the United Nations Framework Convention on Climate Change (UNFCCC), dealing with greenhouse-gas-emissions mitigation, adaptation, and finance. [2]. The most recent report issued by the IPCC is called the Special Report on Global Warming of 1.5 °C (SR15). The report assesses projected impacts at a global average warming of 1.5°C and higher levels of warming. Its crux finding is that meeting a 1.5 °C target is possible but will require deep emissions reductions and rapid, far-reaching and unprecedented changes in all aspects of society [3].

The influential Emissions Gap Report, advocates for the passive house standard in its 2016 edition. This consolidated a recommendation for the standard as a climate mitigation solution in the IPCC 4th assessment report released in 2007 [4]. It is in this context that buildings are central to meeting the sustainability challenge as currently European buildings account for approximately 40% of total energy consumption within the European Union (EU) [5].

The Energy Performance in Buildings Directive (EPBD) mandates that all EU member states build Near Zero Energy Buildings (NZEB) by 2021. The EPBD defines near zero energy buildings, in broad terms, as those with high levels of energy efficiency. The directive further states that the very low amount of energy required should be provided to a very significant degree by energy from renewable sources, preferably produced on or near site [6].

The UK's Climate Change Committee (CCC) is an independent, statutory body established under the Climate Change Act 2008 [7], in 2019 they published a report titled "UK housing: Fit for the future?" [8] states that 'Greenhouse gas emission reductions from UK housing have stalled, and homes across the UK must be improved now to address the challenges of climate change.

The costs of building to a specification that achieves the aims set out in this report are not prohibitive and getting design right from the outset is vastly cheaper than forcing retrofit later'. The CCC is calling for a UK "ultra-energy efficient standard" with a space heating demand of 15-20 kWh/m^2/yr ideally heated with an electric Heat Pump[8].

The International Passive House Standard offers a proven methodology to achieve this standard. The combination of Passive House with heat pump and renewable energy production presents a suitable solution to move to the proposed low/zero carbon objective given the context. Passive Houses focus on energy saving and are designed to have an energy demand that is as low as practically achievable. With such a small amount of energy to be supplied, it is easier to meet the subsequent demand with renewable sources [9]. To meet the Passive House Standard, the airtightness of a building must achieve an air change per hour rate of less than 0.6 air changes at 50 Pascals of pressure (n50), and have ventilation provided by a balanced mechanical ventilation heat recovery system. Existing research in the UK and Ireland has predominantly focussed on Indoor Air Quality (IAQ) and overheating [10]. To date, no research in the UK or Ireland has investigated the relationship between the unique characteristics of certified Passive House buildings and indoor radon concentrations.

This study aims to assess if certified Passive House buildings, with the associated high levels of air tightness coupled with mechanical ventilation, will result in a reduction in indoor radon gas concentrations compared to conventional buildings. It includes the following detailed objectives:

- Evaluating the findings against the target level (TL), Action Level (AL) and the national average;
- Comparing radon distribution levels between upstairs and downstairs;
- Identifying the influence of main construction materials on corresponding radon concentrations;
- Determining the indoor radon concentrations of the Passive House Retrofit standard (EnerPhit) sample; and
- Carrying out case studies on a direct comparison of indoor radon concentrations in a high-risk radon area.

2. PASSIVE HOUSE CRITERIA

Passive House (or Passivhaus) refers specifically to the International Passive House Standard as developed, defined and administered by the Passive House Institute (PHI) in Darmstadt, Germany. Passive House has a very clear set of requirements, so it is possible to check if a building meets the definition of the Passive House Standard. Rigorous modelling and verification are required in the design and construction stages to meet Passive House certification standards. This research will monitor only Passive House buildings certified by the PHI [11].

The Passive House Standard employs a mixed mode ventilation strategy combining a Mechanical Ventilation System and Heat Recovery (MVHR) with summer ventilation/cooling using windows. Mixed mode ventilation allows for Passive House airtightness/air leakage criteria: 0.6 air changes/hour under a blower door test. This minimizes energy loss to the outside, improves insulation performance and reduces moisture ingress into the building fabric. This standard contrasts sharply with natural ventilation methods where sufficient ventilation for occupants is achieved, in part, due to a leaky building fabric. The resultant draughts in naturally ventilated buildings are often exacerbated using open fires which further draw in air for combustion. As concerns about IAQ and health grow, ensuring good IAQ is critical. Available research already indicates that a correctly installed and operating MVHR system has a positive effect on IAQ and humidity levels [12]. The Passive House Standard uses the European air quality category IDA 3 (Moderate IAQ CO_2 level 600–1000ppm) to define MVHR operating parameters along with output that is based on the number of people (30 m^3/h per person) according to DIN 1946, the German standard for ventilation [13]. The Passive House certification criteria set out key metrics for compliance in respect to MVHR including early design consideration, successful installation and commissioned units. This is confirmed by academic research into the performance of the Passive House Standard [12]. The standard is based on compliance of the International Standard for Thermal Comfort ISO 7730 [14].

3. RADON IN BUILDINGS

Radon is a naturally occurring, radioactive gas that results from the decay of uranium in rocks and soils. It is the major source of ionizing radiation exposure to the population. Radon decays to form tiny radioactive particles, some of which stay suspended in the air as colourless, odourless, tasteless gas that can only be measured using special equipment. Normally, when radon is emitted into the open air, it is quickly diluted to harmless concentrations. However, when radon enters an enclosed space, (such as a house) through cracks in floors or gaps around pipes and cables, it can build up to a dangerously high concentration. Inhaled radon particles give a radiation dose that may damage cells in the lung [15].

The WHO has identified radon as a known human carcinogen and has reported a wealth of biological and epidemiological evidence connecting radon exposure and lung cancer [16]. Radon is estimated to cause 1,100 deaths per year in the UK and is the second largest identified cause of lung cancer after smoking [17]. In addition to the UK, approximately

300 cases of lung cancer in Ireland every year can be linked to radon [18]. Considering that the typical person in industrial countries (such as the UK and Ireland) spends approximately 90% of their time indoors,[19] there are surprisingly few academic studies on radon in the home. Monitoring indoor radon is of fundamental importance and this research represents an opportunity to advance an understanding of the effect of increasing energy performance standards and the role of increased airtightness and mechanical ventilation. The Health Protection Agency (HPA) in the UK estimates that with an increase in radon concentration of 100 Becquerels per cubic metre (Bq/m^3), the risk of a smoker developing lung cancer increases by up to 31% with a central estimate of 16% [20]. The HPA advises that homes with smokers or ex-smokers should seriously consider reducing radon levels, where concentrations are measured above the target level (TL) of 100Bq/m^3 because of the substantial risks associated with a combination of smoking and radon exposure [20].

Radon prevention and mitigation

Radon measurements are typically made with two radon detectors, one in the main living area and the other in a regularly used bedroom, reflecting the parts of the home that are most often occupied. Detectors are left in place for three months. Radon is measured in Becquerels per cubic metre of air (Bq/m^3). The governments in both Ireland and the UK recommended an 'action level' for radon in homes as 200 Bq/m^3. Above this level, it is recommended that householders act to reduce their radon levels [16].

Prior to construction, it is not possible to predict the radon concentration in a dwelling. However, probability or risk maps are available, which show the probability of radon concentrations in areas across Ireland and the UK (see Figure 1). These maps are colour coded by concentration level. Indoor radon concentration may be mitigated by two preventative measures: basic radon protection and full radon protection. Basic radon protection is provided by a damp-proof membrane modified and extended to form a radon-proof barrier across the ground floor of the building. Full radon protection comprises a radon-proof barrier across the ground floor and provision for subfloor depressurization (a radon sump) or ventilation (a ventilated subfloor void). The radon sump is not initially activated, rather it is capped and available for use as a secondary measure in case the radon-proof barrier is insufficient for reducing radon levels below the AL of 200Bq/m^3. These requirements for preventative measures are largely similar in both Ireland and the UK, depending on location on the radon risk maps.

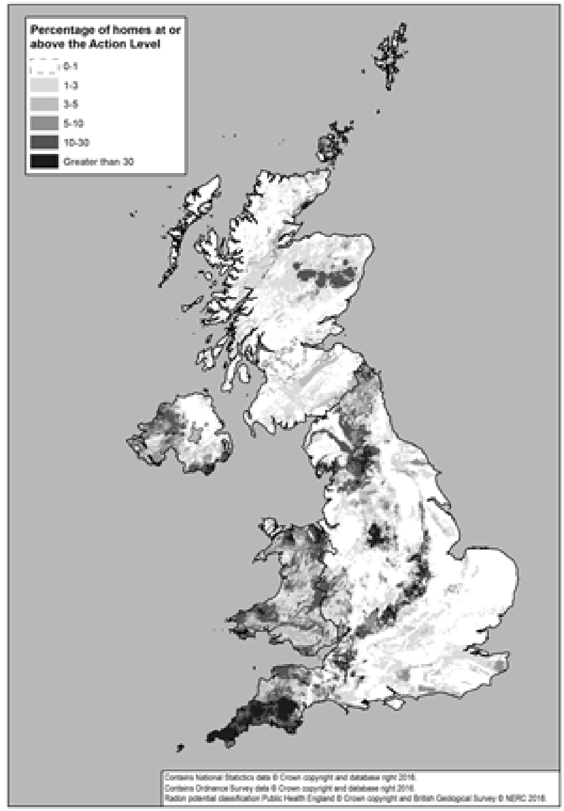

Figure 1: Radon Risk Map of the United Kingdom.

4. SAMPLE SELECTION AND CHARACTERIZATION

The sample in this study comprises 97 certified Passive House buildings in Ireland and the UK and consists of two-house classifications, 92 are passive house certified and five meet the passive house EnerPHit standard (namely passive house retrofit). In addition to these, 25 comparison homes were also selected simply because of their proximity to corresponding certified homes. The oldest of these passive house homes was built in 2005 with the most recent being constructed in 2019. The entire sample is also all two-story domestic dwellings. The largest of these is 455m^2 while the smallest is 122m^2. Of the 97 homes, 54 are of masonry construction and the remaining 43 are of timber frame construction. All the homes are passive house certified and all have a balanced mechanical ventilation heat recovery unit and have an airtightness level (n50) of <0.6 of new homes and the EnerPHit <1.0. The building characteristics and materials are significant, as the most common sources of radon are gas from the soil/ground and off-gassing from building materials containing radon [21]. Building material radon emissions are much lower than radon gas being emitted from soil/ground gas and only apply to such building materials as ground rock and those which originate from ground rock (e.g. sand, soil and cement). Concentrations of radon present in these building materials will vary, depending upon geological origin [22]. The small number of homes retrofitted to the EnerPHit standard are significant as other studies show that energy retrofitting of homes may reduce the potential for ventilation flushing of radon gas from the house, increasing radon levels [23]. Retrofit houses may also have an existing floor that does not include radon protection and sealing the full footprint of the building may prove difficult. Therefore, it is difficult to predict the effect of applying Passive House techniques to existing buildings on indoor radon concentrations: a properly installed and operating MVHR system could reduce the radon level but failing to completely seal the building envelope could increase the radon level.

Radon monitoring

In 2010, the HPA updated its advice on the limitation of human exposure to radon, maintaining the national AL at 200Bq/m^3 and introducing the concept of a TL at 100Bq/m^3 [24] The TL refers to an annual average concentration of 100Bq/m^3 or below as the ideal level acceptable in a building. The HPA, WHO and most international governments recognize that homes which exceed the radon AL (200Bq/m^3) should reduce their radon levels with immediate effect. In this study, indoor radon levels were measured by CR-393 alpha track diffusion radon gas detectors placed in the main living area (Room 1) and the main bedroom (Room 2) for just over three months in three different stages from October 2017 to June 2019. Radon results are presented as an annual average using the seasonal adjusted average (SSA) method. The test results are compared with the existing national averages data on radon both in Ireland and the UK.

5. RADON TESTING RESULTS

Radon measurements were completed in a total of 123 homes; 97 certified (including 5 EnerPhit) passive house buildings and 25 comparison homes. None of the 97 certified passive homes surveyed had radon concentrations exceeding the 200 Bq/m^3 (see Figure 3) national Reference Level. Only 6.79% of the sample breached the target level of 100 Bq/m^3. The maximum concentration measured was 149 Bq/m^3 in a home in Northern Ireland located in a defined higher risk area.

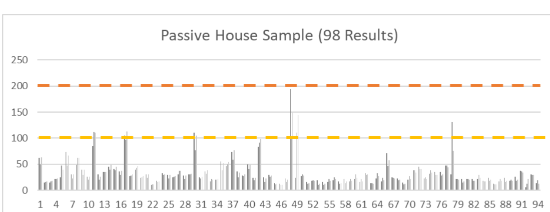

Figure 2: Passive House Sample (97 homes) with AL and TL shown with dashed lines.

The Environmental Protection Agency (EPA) carried out the National Radon Survey (NRS) of Ireland between 1992 and 1999 [18]. The survey characterized areas of Ireland in terms of their radon risk and one of the key findings was that the geographic weighted national average indoor radon concentration at that time was 89 Bq/m^3. Since then, several developments have taken place in Ireland that are likely to have impacted on the national average radon concentration. These include the introduction of amended Building Regulations in 1998, requiring radon preventive measures in new buildings in High Radon Areas (HRAs), between 1999 and 2014 the number of dwellings in Ireland increased dramatically by an estimated 47%. To re-assess the national average indoor radon concentration, a survey protocol was carried out in 2015, which would measure radon in a sample of homes as the representative of radon risk and geographical location. This new national average was published in 2017 and could then be used to assess the effectiveness of the measures that have impacted on this metric since it was first established in the 2002 NRS [18]. The results showed that the national average indoor radon concentration for homes in Ireland was 77 Bq/m^3, a decrease from the 89 Bq/m^3 reported in the 2002 NRS. This figure of 77 Bq/m^3 is now a baseline metric for the National Radon Control Strategy (NRCS) [18].

Radon levels against national average

The average indoor radon level based on the 98 certified passive homes monitored in this study is 36 Bq/m^3 as shown in Table 1. It can be directly compared with the national average of 77 Bq/m^3. The radon level of certified passive homes is directly compared with the non-passive houses (namely comparison homes), which were also monitored in this study. The average of comparison homes was found to be 88 Bq/m^3 which is broadly in line with NRS.

Table 1: Radon results showing the EPA 2015 NRS, the comparison sample and finally the Passive House sample.

Metric	EPA 2015 NRS	Comparison Sample	PH Sample
Number of homes measured	649	25	97
No. of homes >200 Bq/m3	8%	8%	0%
No. of homes >100 Bq/m3	25%	16%	7%
Minimum concentration measured (Bq/m3)	14	21	10
Maximum concentration measured (Bq/m3)	1393	598	149
Seasonally adjusted annual average for Sample	77	88	36

Radon distribution

The single most striking observation to emerge from the data shows a difference in radon distribution between upstairs and downstairs when compared against regular housing. In previous UK research, radon levels were found to be typically 35% lower on first floor bedrooms compared to ground floor living rooms [25]. In this research, the radon concentrations between both floors tested interestingly found that levels were only 6% lower on the first-floor bedrooms compared to ground floor living rooms. This sample included the analysis of 344 standard two-story homes from the EPA 2015 NRS and the Passive House sample of 97 two-story homes, which presented this different radon distribution. Distribution ratios shown in Table 2 of the bedroom/living room radon levels in the standard two-story homes presented as gaussian distribution (mean 0.79, median 0.74 with a standard deviation of 0.37). The results of the certified passive house sample are significantly anomalous (mean 1.03, median 0.92 with a standard deviation of 0.56).

Table 2: Radon distribution results comparing the passive house sample tested in this study against the EPA NRS 2015.

Study	No of Samples	Average Ratio	Mean Ratio	Standard Deviation
National Radon Study (2 Storey)	344	0.79	0.74	0.37
PH Study	97	1.03	0.92	0.56

A possible reason for the difference may lie in the fact that the Passive house standard has a defined specification for airtightness and MVHR systems, unlike much of the standard dwellings. In addition to this, there is a consistent framework on design, installation and commissioning of these systems. This quality assurance coupled with typical layout of a two-storey dwelling combine to produce the lower indoor concentrations and closer distribution levels between upstairs and downstairs.

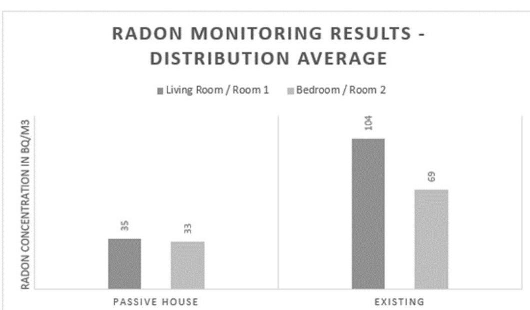

Figure 3: Radon monitoring results Distribution Average.

Radon from building materials

While the influence of building materials on indoor radon concentrations is recognized, there is a paucity of quantitative data representing the structural contribution to domestic radon. A figure on 20 Bq/m^3 has recently been suggested for the contribution from building materials to indoor radon concentrations [21]. In this study, 54 are constructed from masonry and the remining 43 are of timber frame construction. The analysis results shown in Figure 5 reveal that the timber frame group has a slightly lower radon level than the masonry group. This corresponds with previous research [25]. However, as the number of houses investigated in this research was relatively small and it was not the key focus of the research, the results should be treated with caution.

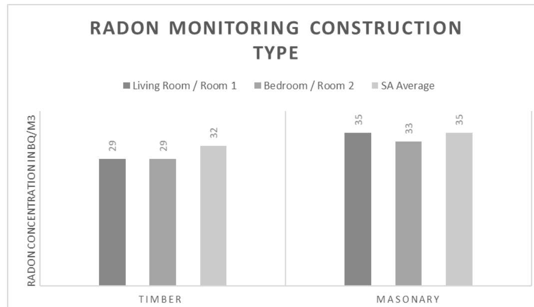

Figure 4: Radon Monitoring Construction Materials.

A total of 10 comparative case studies were also carried out, which were in known high risk areas. For each case study, the comparison is between a certified passive house and the home directly next door. The findings here are significant as conventional homes demonstrate elevated levels in all 10 case studies. As shown below in Figure 6, a clear differentiation is also found in levels among 50% of the case studies between the two groups.

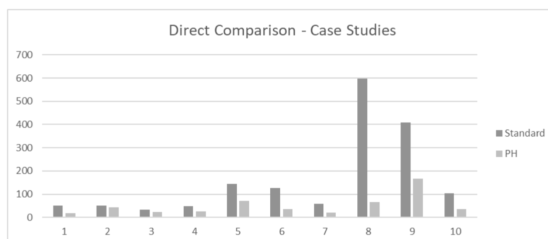

Figure 5: Direct comparative case studies.

The figure above illustrates that in the five case studies with the clear differentiation, (5, 6, 8, 9 and 10), the conventional home sample all have levels on or above the Action Level of 100 Bq/m^3. From the figure above, it is also seen that Homes 8 and 9 have significantly elevated levels 598 Bq/m^3 and 400 Bq/m^3. By comparison, the corresponding passive houses next door in both case studies have levels of 67 Bq/m^3 and 166 Bq/m^3, respectively.

6. CONCLUSION

Radon is perhaps the most dangerous contaminant within the IAQ spectrum. The accumulation in houses can increase the risk of lung cancer, especially in individuals who smoke. This study presents the key findings of a larger PhD research project into the indoor radon levels in Passive House buildings compared national averages in conventional buildings. The results support the hypothesis that certified Passive House buildings perform better in respect to indoor radon concentrations compared to conventional homes given less airtightness and no MVHR systems. The research also consolidates this with individual findings. The clearest illustration of this was in the presentation of the ten case studies, which highlighted elevated levels in the comparison homes against all ten Passive House buildings coupled with five distinctive contrasting results showing clear differentiation from the corresponding comparison home. The radon distribution results indicate that the passive house framework for quality assurance of the design, installation, and commissioning promote a properly functioning MVHR system. This will result in more extract on the ground floor thus reducing the ground floor radon level and lowering the distribution gap. On the other hand, the findings on the relationship with construction materials and radon concentrations are not statistically significant to make claims about background radon emissions.

This project is the first comprehensive investigation of indoor radon in certified passive house buildings in the UK and Ireland. The analysis of the radon levels undertaken here has extended our knowledge of the effect of airtightness and mechanical ventilation heat recovery systems combined in a clear methodology such as the passive house standard. The findings of this study have important implications for future practice. It illustrates the value of having a clear methodology of quality assurance (integral to the passive house process). Passive House exhibits better radon performance which is ascribed to the combination of reduced air infiltration combined with mechanical ventilation. Other possible implications include:

1. There is the need for quality assurance in design and construction.
2. The potential offered by ensuring the MVHR system is balanced such that the house is at a slight positive pressure.

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